

Vortices in brain waves

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Interactions by mutual excitation in neural populations in human and animal brains create a mesoscopic order parameter that is recorded in brain waves (electroencephalogram, EEG). Spatially and spectrally distributed oscillations are imposed on the background activity by inhibitory feedback in the gamma range (30-80 Hz). Beats recur at theta rates (3-7 Hz), at which the order parameter transiently approaches zero and microscopic activity becomes disordered. After these null spikes, the order parameter resurges and initiates a frame bearing a mesoscopic spatial pattern of gamma amplitude modulation that governs the microscopic activity, and that is correlated with behavior. The brain waves also reveal a spatial pattern of phase modulation in the form of a cone. Using the formalism of the dissipative many-body model of brain, we describe the null spikes and the accompanying phase cones as vortices.

I. INTRODUCTION

The dissipative quantum model of brain predicts two main features of neurophysiological data [1]: the coexistence of physically distinct amplitude modulated (AM) and phase modulated (PM) patterns correlated with categories of conditioned stimuli and the remarkably rapid onset of AM patterns into irreversible sequences that resemble cinematographic frames. These features of the brain activity are observed in laboratory by means of imaging of scalp potentials (electroencephalograms, EEGs) and of cortical surface potentials (electrocorticograms, ECoGs) of animal and human from high-density electrode arrays. The mesoscopic neural activity of neocortex appears indeed consisting of the dynamical formation of spatially extended neuronal domains in which widespread cooperation supports brief epochs of patterned synchronized oscillations, which have been demonstrated to occur in the 12 – 80 *Hz* range (β and γ ranges). They re-synchronize in frames at frame rates in the 3 – 12 *Hz* range (θ and α ranges) [1, 2, 3, 4, 5]. These patterns, or “packets of waves”, appear often to extend over spatial domains covering much of the hemisphere in rabbits and cats [6, 7], and over the length of a 64×1 linear 19 *cm* array [2] in human cortex with near zero phase dispersion [8, 9]. Synchronized oscillation of large-scale neuronal assemblies in β and γ ranges have been detected also by magnetoencephalographic (MEG) imaging in the resting state and in motor task-related states of the human brain [10]. The patterns of phase-locked oscillations are intermittently present in resting, awake subjects as well as in the same subject actively engaged in cognitive tasks requiring interaction with environment, so they are best described as properties of the background activity of brains that is modulated upon engagement with the surround.

Neither the electric field of the extracellular dendritic

current nor the extracellular magnetic field from the high-density electric current inside the dendritic shafts, which are much too weak, nor the chemical diffusion, which is much too slow, appear to be able to fully account for the observed cortical collective activity [1, 11]. On the contrary, it turns out that the many-body dissipative model [12] is able to account for the dynamical formation of synchronized neuronal oscillations [1]. This will not be illustrated again here (the reader may find detailed discussion in [1, 12, 13]). We only recall that each AM pattern is described to be consequent to spontaneous breakdown of symmetry triggered by external stimulus [12, 14] and is associated with one of the quantum field theory (QFT) unitarily inequivalent ground states [1, 12]. Their sequencing is associated to the non-unitary time evolution implied by dissipation [1, 12]. In this paper we focus our attention on a crucial neural mechanism, that we deduced from experimental observations of a pattern called “Coordinated Analytic Phase Differences” (CAPD) [3, 4, 5, 6, 7], consisting in the fact that the event that initiates the transition to a perceptual state is an abrupt decrease in the analytic power of the background activity to near zero, depicted as a null spike, associated with the concomitant increase of spatial variance of analytic phase. The null spikes tend to recur aperiodically at rates in the theta (3 – 7 *Hz*) and alpha (8 – 12 *Hz*) ranges. By use of the Hilbert transform, the local structure of CAPD is visualized in the real and imaginary parts, $a(x)$ and $b(x)$, respectively, of the ECoG sampled wave function $\psi(x)$ in the selected spectral pass band

$$\psi(x) = \mathbf{A}^2(x)e^{i\phi(x)}, \quad (1)$$

where $x \equiv (x, y, t)$ in the two surface dimensions of cortex (3 dimensions for the microscopic level of networks), and

the analytic power $\mathbf{A}^2(x)$ and the analytic phase $\phi(x)$ are

$$\mathbf{A}^2(x) = \sqrt{a^2(x) + b^2(x)}, \quad (2)$$

$$\phi(x) = \arctan \frac{b(x)}{a(x)}, \quad (3)$$

respectively. During periods of high amplitude the spatial deviation of phase (SD_X) is low and the phase spatial mean tends to be constant within frames and to change suddenly between frames, indicating coherence and coordinated phase differences. $\mathbf{A}^2(x)$ forms a feature vector that serves as our order parameter (see below and Refs. [1, 13]).

The reduction in the amplitude of the spontaneous background activity induces a brief state of indeterminacy in which the significant pass band of the electrocorticogram (ECoG) is near to zero and the phase of ECoG is undefined (Figure 1).

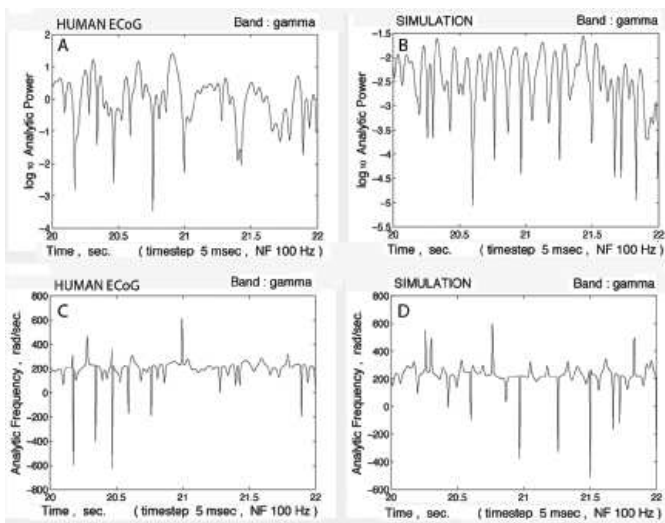


Figure 1. The temporal patterns of null spikes are illustrated; each spike initiates a spatial phase cone. A. The logarithm of the analytic power (four ECoG signals superimposed from an 8x8 array) in the gamma range (25-50 Hz) shows the downward null spikes demarcating onsets of cones at irregular intervals. C. The spikes in analytic phase coincide with the null spikes in power; the differences between signals reflect the high spatial variance contributed by the cones. B. The statistical properties of null spikes are replicated by cumulatively summing Gaussian noise and applying to the signal the same band pass filter (1/4 to 1/2 the Nyquist frequency, 100 Hz). D. The spikes in analytic phase coincide with the null spikes in power.

The cortex can be driven across such a “phase transition” process to a new AM pattern by the stimulus arriving at or just before this state. The observed velocity of spread of phase transition is finite, i.e. there is no “instantaneous” phase transition. Experimental evidence of CAPD over large cortical areas indicates that the neuronal correlation length would cover an entire cerebral

hemisphere virtually instantaneously (practically without delay in the gamma activity), if measured at the critical transition. Between the null spikes the cortical dynamics is (nearly) stationary for $\sim 60 - 160$ ms. This is called a frame. The transitions by which they form are shorter by an order of magnitude.

In this paper we discuss such a mechanism and describe, in the formalism of the dissipative model, the observed occurrence of phase cones and the dynamic formation of vortices in brain waves. The phase cone is a spatial phase gradient that is imposed on the carrier wave of the wave packet in a frame by the propagation velocity of the largest axons having the highest velocity in a distribution. The location of the apex is a random variable across frames that is determined by the accidents of where the null spike is lowest and the background input is highest. The null spike has rotational energy at the geometric mean frequency of the pass band, so it is called a vortex. The vortex occupies the whole area of the phase-locked neural activity of the cortex for a point in time. One more observed feature is the random variation from each frame to the next of the slope of the conic phase gradient, negative with explosion, positive with implosion. The negative gradient could be explained in conventional neurodynamics (e.g. in terms of a pacemaker), but not the positive gradient. Also, there is no explanation in the conventional framework of why both gradients, the positive and the negative one, occur. These features have been documented as markers of the interface between microscopic and mesoscopic phenomena.

In the process of non-instantaneous phase transitions (as those observed in brain) the dissipative model predicts the existence of vortex singularity associated (at the vortex core) with the abrupt decrease (null spike) of the order parameter (the analytic amplitude) and the concomitant increase of spatial variance of the phase field (the analytic phase). The resulting phase cones present both phase gradients, the positive and the negative one, as in the observations.

Phase transitions and vortex solutions in the dissipative model are discussed in Section II where it is shown how the model predicts the observed feature of null spikes. Heat dissipation involved in the disappearance/emergence of coherence is discussed in Section III. In Section IV it is presented the discussion of size, number and time dependence of transient non-homogeneous structures appearing during non-instantaneous phase transitions, such as those observed in brain. The formation of imploding and exploding phase cones is shown to be allowed, as indeed deduced from observations. Section V is devoted to final remarks and conclusions.

II. PHASE TRANSITIONS, VORTEX SOLUTIONS AND NULL SPIKES

We start by recalling that in the dissipative model of brain spontaneous breakdown of the rotational symmetry

of electrical dipoles of water and other molecules [12, 15] implies the existence of Nambu-Goldstone modes (NG) [16, 17] which in such a context have been called the dipole wave quanta (DWQ), say $P(x)$ and $P^\dagger(x)$. The non-vanishing polarization density $\mathcal{P} = \rho\delta$, where ρ and δ are the charge density and the (average) dipole length, is expressed in terms of these field modes [18] and the system ground state is obtained in terms of coherent condensation of the DWQ. One then considers the spontaneous breakdown of the phase symmetry and the charge density wave function $\sigma(x)$ is written [18] as

$$\sigma(x) = \sqrt{\rho(x)} e^{i\theta(x)}, \quad (4)$$

with real $\rho(x)$ and $\theta(x)$. The “phase” $\theta(x)$ is the NG field associated with the breakdown of global phase symmetry. The boson condensation of the field $\theta(x)$ in the system ground state is formally described by the transformation

$$\theta(x) \rightarrow \theta(x) - \frac{e_0 v^2}{Z} f(x). \quad (5)$$

The c-number condensation function $f(x)$ satisfies the same equation satisfied by the $\theta(x)$ field, i.e. $\partial^2 f(x) = 0$. The constant Z is the wave function renormalization constant, e_0 and v are the electron charge and the constant entering the symmetry breakdown condition $\langle 0|\rho(x)|0 \rangle = v \neq 0$ [18, 19, 20].

Coherent domains of finite size are obtained by non-homogeneous boson condensation. The condensate is described by the function $f(x)$ which acts as a “form factor” specific for the considered domain [20, 21, 22, 23]. One can show [18, 19] that mathematical consistency requires that the electromagnetic vector potential $a_\mu(x)$ has then to satisfy the equation

$$(\partial^2 + m_V^2) a_\mu(x) = \frac{m_V^2}{e_0} \partial_\mu f(x). \quad (6)$$

We adopt the gauge condition $\partial^\mu a_\mu(x) = 0$. Eq. (6) is the classical Maxwell equation for the massive vector potential a_μ (m_V is its mass). The classical ground state current $j_{\mu,cl}$ turns out to be

$$j_{\mu,cl}(x) \equiv \langle 0|j_\mu(x)|0 \rangle = m_V^2 \left[a_\mu(x) - \frac{1}{e_0} \partial_\mu f(x) \right], \quad (7)$$

and we have $\partial^\mu j_{\mu,cl}(x) = 0$. The term $m_V^2 a_\mu(x)$ is the well known *Meissner current*, while $\frac{m_V^2}{e_0} \partial_\mu f(x)$ is the *boson current*.

The mesoscopic field and current are thus given in terms of the boson transformation function. It is also remarkable that the classical current is related with $\partial_\mu f$, i.e. with variations in the boson transformation function.

The important point is that such a condensation function $f(x)$ has to carry some topological singularity in order for the condensation process to be physically detectable. The function $f(x)$ carrying a topological singularity is not single-valued and thus is path-dependent:

$$[\partial_\mu, \partial_\nu] f(x) \neq 0, \quad \text{for certain } \mu, \nu, x. \quad (8)$$

On the other hand, observables may be influenced by gradients in the Bose condensate and thus $\partial_\mu f$ is related with observables and therefore has to be single-valued, i.e. $[\partial_\rho, \partial_\nu] \partial_\mu f(x) = 0$. A regular function $f(x)$ would produce a condensation which could be easily “gauged” away by a convenient field transformation. From (6) we obtain $a_\mu(x) = \frac{1}{\partial^2 + m_V^2} \partial_\mu f(x)$. When $f(x)$ is regular, this gives $\partial^2 a_\mu(x) = 0$ since $\partial^2 f(x) = 0$. Thus Eq. (6) implies $a_\mu(x) = \frac{1}{e_0} \partial_\mu f(x)$ for regular $f(x)$, which in turn implies zero classical field ($F_{\mu\nu} = \partial_\mu a_\nu - \partial_\nu a_\mu$) and zero classical current ($j_{\mu,cl} = 0$) since the Meissner and the boson current cancel each other. It is indeed well known [24] that the gauge field a_μ is expelled out of the ordered domain region (it is there vanishing) where the order parameter is of course non-zero and $f(x)$ does not have singularities. On the contrary, the gauge field is non zero in the regions where $f(x)$ presents non-trivial topological singularities such as line singularities, e.g. on the line $r = 0$ in the core of a vortex: we have there the “normal” (disordered) state rather than the ordered one and the non-vanishing massive gauge field there propagates (the Anderson-Higgs-Kibble mechanism) [24, 25]. On the boundaries between the normal and the ordered regions the phase field gradients are non-zero. Instead they are zero in the normal region, i.e. in the vortex core. Consistently with this scenario, one can also show [20, 22, 23] that the phase transition from one state space to another (unitarily inequivalent) one can be only induced by a singular boson transformation function $f(x)$. This is the reason why topologically non-trivial extended objects, such as vortices, appear in the processes of phase transitions [20, 22, 23]. Stated in different words, this means that phase transitions driven by boson transformations are always associated with some singularities in the field phase. We thus recognize that in the brain the null spike (the observed abrupt decrease in the order parameter and the concomitant increase in the phase field gradients in the phase transition from an AM amplitude to another one) is indeed characterized by the topological singularity of the function $f(x)$. In the case of phase symmetry summarized above, the stationary function $f(x)$ solution of our problem carries a vortex singularity and is given by

$$f(x) = \arctan \left(\frac{x_2}{x_1} \right). \quad (9)$$

Eq. (9) shows that the phase is undefined on the line $r = 0$, with $r^2 = x_1^2 + x_2^2$, consistently with the observed phase indeterminacy in the process of transition between two AM pattern frames. As usual in these cases, as a result of the single-valuedness of $\sigma(x)$ the topological singularity is characterized by the winding number n : $\oint \nabla f \cdot d\mathbf{l} = \frac{2\pi}{e_0} n$, $n = 0, \pm 1, \pm 2, \dots$, when the integration is performed along the closed circle $(0, 2\pi)$ (flux quantization).

The stimulus arriving at or just before the abrupt decrease of analytic power drives the cortex across the phase transition process to the new AM pattern. As remarked

elsewhere [1], the dissipative model predicts that the response amplitude depends not on the input amplitude, but on the intrinsic state of the cortex, specifically the degree of reduction in the power and order of the background brown noise. As a matter of fact, such a feature is one of the merits of the mechanism of spontaneous breakdown of symmetry where the external stimulus (as in the case of the brain) only acts as a trigger, the correlated phase regime being reached as the effect of the system inner dynamics. This explains the observed lack of invariance of AM patterns with invariant stimuli [1, 4, 5, 6, 7]. The power is indeed not provided by the input, exactly as the dissipative model predicts, but by the pyramidal cells.

We also observe that the initial site where non-homogeneous condensation starts (the phase cone apex) is not conditioned by the incoming stimulus, but is randomly determined by the concurrence of a number of local conditions, such as where the null spike is lowest and the background input is highest, in which the cortex finds itself at the transition process time. The apex is never initiated within frames (in the broken symmetry phase or ordered region), but between frames (during phase transitions), as it is indeed predicted by the dissipative model (vortices occur during the critical regime of phase transitions). The null spike appears in the band pass filtered brown noise activity and can be conceived as a *shutter* that blanks the intrinsic background ECoG. When the order parameter goes to zero the microscopic activity (of the background state) does not decrease but, consistently with the model description, it becomes disordered, unstructured (fully symmetric). In such a state of very low analytic amplitude, the analytic phase is undefined, as it is indeed at the center line of the vortex core, and the system, under the incoming weak sensory input, may re-set the background activity in a new AM frame, if any, formed by reorganizing the existing activity, not by the driving of the cortical activity by input (except for the small energy provided by the stimulus that is required to force the phase transition). The analytic amplitude decrease repeats in the theta or alpha range, independently of the repetitive sampling of the environment by limbic input. Consistently with observations, in the dissipative model the reduction in activity constitutes a singularity in the dynamics at which the phase is undefined. The aperiodic shutter allows opportunities for phase transitions.

III. HEAT DISSIPATION AND DISAPPEARANCE/EMERGENCE OF COHERENCE

We have already commented upon the remarkable interplay between the emergence of mesoscopic field and currents and the microscopic phenomenon of boson condensation (cf. the discussion after Eqs. (6) and (7)). We further observe that the neural mechanism of perception

depends on repeated transfer of mesoscopic energy to microscopic energy and vice-versa as the basis for the disintegration of a mesoscopic AM pattern and the formation of a new one, respectively. In the dissipative model these energy transfers are controlled by the time derivative of the number, \dot{N} , of the θ phase field condensate [1, 12]:

$$dE = \sum_k E_k \dot{N}_k dt = \frac{1}{\beta} dS. \quad (10)$$

Eq. (10) holds provided changes in the inverse temperature β are slow, which is what actually happens in mammalian brain which keep their temperature nearly constant. It relates the changes in the energy $E \equiv \sum_k E_k N_k$ and in the entropy S implied by the minimization of the free energy at any t . Here E_k and N_k denote the energy and the number of the NG phase field excitations of momentum k . As usual heat is defined as $dQ = \frac{1}{\beta} dS$. We thus see how, through the variations in time of the phase field condensate, the entropy changes and heat dissipation involved in the disappearance/emergence of the coherence (ordering) associated to the AM patterns turns into energy changes. Heat dissipation appears indeed to be a significant variable in laboratory observations. We remark that, consistently with observations, the variations $\partial_\mu f$ of the θ phase field condensate is detectable at the mesoscopic level only by the variations of the analytic phase.

Also concerning the mesoscopic/microscopic interplay, it has to be remarked that the vortex solution in the dissipative model, although is dynamically generated through the non-homogeneous boson condensation mechanism, which is a truly quantum mechanism, manifests itself as a solution of non-linear *classical* equations. This a general feature of QFT, where many kinds of topologically non-trivial solutions of classical field equations (soliton solutions) are described as mesoscopic “envelops” of microscopic boson condensates (for a detailed discussion on the quantum/classical interplay in field theories with topologically non-trivial solutions see [26]; see also [19, 20, 27]). The dissipative quantum model of brain thus provides classical mesoscopic phenomena originated from the underlying quantum dynamics. As elsewhere stressed [1, 12, 13], in such a model the neurons, the glia cells and other physiological units are *not* quantum objects. The quantum degrees of freedom are those associated to the dipole vibrational field and to other fields such as the phase field.

Summarizing, the spatial gradient of $f(x)$ in the Bose condensate of the $\theta(x)$ “phase” field accounts for the phase cone which is indeed a spatial phase gradient imposed on the carrier wave of the wave packet. The vortex solution arises as an effect of non-homogeneous condensation of the phase field $\theta(x)$, which spans (almost) the whole system since it is a (quasi-)massless field (it is a collective mode). This explains the fact that in its life-time the vortex is observed to occupy the whole area of the phase-locked neural activity of the cortex. In this connection, it is interesting to comment on the size, number and

time dependence of transient non-homogeneous structures appearing during non-instantaneous phase transitions (lasting a finite time interval), such as those observed in brain. We consider this in the next Section and we find that converging and diverging (imploding and exploding) phase cones are formed, as indeed deduced from observations.

IV. PHASE CONES AND CRITICAL REGIME IN THE DISSIPATIVE MODEL

Transition processes occurring in a finite span of time in which the formation of defects (e.g. vortex strings) occurs, have been studied by numerical simulations and theoretical modeling in a number of problems of physical interest [23, 28, 29]. In these processes, a maximally stable new configuration is attained after a certain lapse of time since the transition has started. The system is said to be in the critical or Ginzburg regime during such a lapse of time. In the critical regime one deals with the matter field (the Higgs field in elementary particle physics) condensate and the NG ($\theta(x)$ phase field) condensate. We have considered the last one in the discussion above. Enough reliable information on the critical regime behavior of the former one is provided by using the harmonic approximation for the evolution of the order parameter v , which is now assumed to be space-time dependent (non-homogeneous Higgs condensate) [22, 23, 28]. By resorting to such an approximation in our present brain problem, we expand the v field into partial waves:

$$v(x, t) = \sum_{\mathbf{k}} \{u_{\mathbf{k}}(t)e^{i\mathbf{k}\cdot\mathbf{x}} + u_{\mathbf{k}}^{\dagger}(t)e^{-i\mathbf{k}\cdot\mathbf{x}}\}. \quad (11)$$

In general, v and u depend also on the temperature. However, we will omit the dependence on temperature since this does not affect our discussion. In the harmonic potential approximation of the the Ginzburg-Landau (GL) formalism we have the equations for the parametric oscillators $u_{\mathbf{k}}$ [30] (see also [22, 23]) for each k -mode ($k \equiv \sqrt{\mathbf{k}^2}$):

$$\ddot{u}_{\mathbf{k}}(t) + (\mathbf{k}^2 - m^2)u_{\mathbf{k}} = 0. \quad (12)$$

Note that the sign of the mass term m^2 is consistent with the occurrence of spontaneous breakdown of symmetry [23, 31]. The oscillator frequency is

$$M_k(t) = \sqrt{\mathbf{k}^2 - m^2(t)}. \quad (13)$$

$M_k(t)$ is required to be real for each k and, in full generality, in Eq. (13) we are assuming that m^2 may depend on time. The reality condition on $M_k(t)$ is satisfied provided at each t , during the critical regime time interval, it is

$$\mathbf{k}^2 \geq m^2(t), \quad (14)$$

for each k -mode. This turns out to be a condition on the k -modes propagation. Let $t = 0$ and $t = \tau$ denote the times at which the critical regime starts and ends, respectively. For a given \mathbf{k} , Eq. (14) holds up to a time τ_k after which $m^2(t)$, for $t > \tau_k$, is larger than \mathbf{k}^2 . The corresponding k -mode can propagate in a span of time $0 \leq t \leq \tau_k$. Thus the “effective causal horizon” [32, 33] can happen to be inside the system (possible formation of more than a domain) or outside (single domain formation) according to the time occurring for reaching the boundaries of the system is longer or shorter than the allowed propagation time. This determines the dimensions to which the domains can expand.

The value of τ_k is given when the explicit form of $m^2(t)$ is assigned. One may then consider to model the time dependence of $m(t)$ [23] in a way to allow defect (i.e. vortex) formation. We thus choose $m^2(t)$ to be:

$$m^2(t) = m_0^2 e^{2h(t)}. \quad (15)$$

The function $h(t)$ is assumed to be positive, monotonically growing in time from $t = 0$ to $t = \tau$. The correlation propagation time is implicitly given by:

$$h(\tau_k) = \ln\left(\frac{k}{m_0}\right) \propto \ln\left(\frac{L}{\xi}\right), \quad (16)$$

$h(\tau_k)$ resembling the commonly called string tension [33]. In Eq. (16), ξ is the correlation length corresponding to the k -mode propagation and $L \propto m_0^{-1}$. L acts as an intrinsic infrared cut-off. Small k values are indeed excluded, due to Eq. (14), by the non-zero minimum value of m^2 . Correspondingly, long wave-lengths are precluded, i.e. only domains of finite size can be obtained. At the end of the critical regime the correlation may extend over domains of linear size of the order of $\lambda_k \propto m^{-1}(\tau)$.

Our model is further specified by choosing an explicit analytic expression for $h(t)$. We choose [23]:

$$h(t) = \pm \frac{at}{bt^2 + c}, \quad (17)$$

where a, b, c are (positive) parameters chosen so to guarantee the correct dimensions and the correct behavior in time. We denote their ratios by $c/a\lambda \equiv \tau_Q$, $a\lambda/b \equiv \tau_0$, with λ an arbitrary constant. We note that $h(\tau_Q) = h(\tau_0)$. The time derivative of $h(t)$, and thus of $m^2(t)$, is zero at $t = \tau = \pm\sqrt{\tau_Q\tau_0}$. τ thus plays the role of the equilibrium time scale. We observe that

$$h(t) = \pm \frac{1}{\lambda\tau_Q} \frac{1}{1 + \frac{t^2}{\tau^2}} t \approx \pm \frac{\Gamma}{2} t, \quad (18)$$

for $t^2/\tau^2 \approx 1$, with $\Gamma \equiv 1/\lambda\tau_Q$.

The number of defects (of vortices) n_{def} possibly appearing during the critical regime is given in the linear approximation by [23, 33]:

$$n_{def} \propto m^2(\tau) \approx m_0^2 |\tau/\lambda\tau_Q|. \quad (19)$$

We observe that the size of the vortex core is given by $(m(t))^{-1}$ and thus Eqs. (15) and (18) show that such a size evolves in time as $e^{\mp\Gamma t}$, $t < \tau$ ($t < \tau_k$ for the k -mode). This means that we have both, converging (imploding) and diverging (exploding) regimes, as indeed found in laboratory observations of the phase cone behaviors. Since the “normal” state is confined to the vortex core, the shrinking of such a region (imploding regime) may signal that long range correlation, i.e. ordering, is prevailing (the vortex is “squeezed out”); in the opposite case of enlargement of the vortex core (exploding regime), local correlations (disorder) prevail. This agrees with the postulate reached on the basis of laboratory observations according to which implosion or explosion is obtained if the long axon connections or the local connections predominate, respectively [34].

V. FINAL REMARKS AND CONCLUSION

As a final comment we remark that Eq. (18) shows that the \pm signs in Eq. (17) amount to working with both elements of the basis $(e^{+\Gamma/2 t}, e^{-\Gamma/2 t})$, as indeed required by mathematical correctness. In this sense, the \pm double sign cannot be avoided in the model choice of $h(t)$. From a physical point of view, it is equivalent to

working with time evolution pointing in one given time direction (say the $t > 0$ arrow of time) and with its “time-reversed” copy or image. This is perfectly consistent with one of the main features of the dissipative model where time-reversed excitations are introduced, thus “doubling” the system degrees of freedom [35], so that one is led to consider the time-reversed image of the system, its “Double”. It is interesting to observe that such a model feature finds a connection with the laboratory observation of the exploding/imploding feature in the phase cone behavior. The description of the vortex singularities appearing in the process of phase transitions turns out to be crucial in the understanding of the nature of the engagement of the subject with the environment in the action-perception cycle. By the continual updating of the meanings of the flows of information exchanged in its relation with the environment, the brain proceeds from information to knowledge in its own world as it is known by itself that we describe as its Double [27].

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